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Microturbulence reduction during internal transport barrier discharges in DIII-D

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Abstract. Increased plasma confinement, temperature and fusion reactivity in negative central shear (NCS) discharges in DIII-D are accompanied by reduced core electrostatic microturbulence. The microturbulence reduces as the local radial electric field and shear increases, consistent with a theoretical model incorporating turbulence stabilization by shear radial electric field. Reduced turbulence and the associated anomalous transport reduction leads to further increased radial electric field shear via a steeper pressure gradient and reduced momentum transport. During the H-mode phase of a core transport barrier discharge, the microturbulence is virtually quenched in the core. Increasing evidence indicates that the transport barrier initially forms in the plasma interior when $E \times B$ shear is large.

1. Introduction

Recent experimental and theoretical progress in magnetic confinement fusion has developed a discharge which possesses greatly reduced thermal and/or particle transport which is in some cases quantitatively consistent with neoclassical predictions [1–3]. The new configuration is achieved through simple yet effective control of the plasma current profile, by keeping the peak current density away from the magnetic axis resulting in hollow or nearly flat safety factor (q-) profiles. This magnetic configuration is referred to in DIII-D as negative central magnetic shear (NCS) and such discharges which develop a core transport barrier have been found to possess highly sheared $E \times B$ profiles which play a role in suppressing turbulence [4].

Experimental evidence from DIII-D and other tokamaks indicates that turbulent fluctuations decrease significantly during high performance NCS discharges [5, 6] as compared to discharges with a peaked current profile and similar auxiliary heating. This is due to the formation of a core transport barrier. Large plasma rotation and internal pressure are measured in core transport barrier discharges indicating the presence of a large and highly sheared radial electric field, which is able to reduce turbulence through nonlinear decorrelation and linear stabilization [4]. The unique feature which the modified current profile provides is spontaneous and self-consistent evolution of the shear and transport profiles early in the discharge by suppression of turbulence driving instabilities such as ballooning modes and sawteeth [7].

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2. NCS discharges and turbulence

Early application of neutral beam injection (NBI) heating during the current ramp of a discharge slows inward current diffusion resulting in a plasma current profile that is hollow or flat and a safety factor (q-) profile which is similarly hollow or flat from the centre out to a radial position, which can be a significant fraction of the plasma radius. Figure 1 shows the plasma current, NBI heating, central and minimum values of q, and the ion temperature at various radii from the core out to approximately one half the minor radius as a function of time during a NCS discharge. The early low-power and subsequent high-power phases of the discharge are noted in the figure.

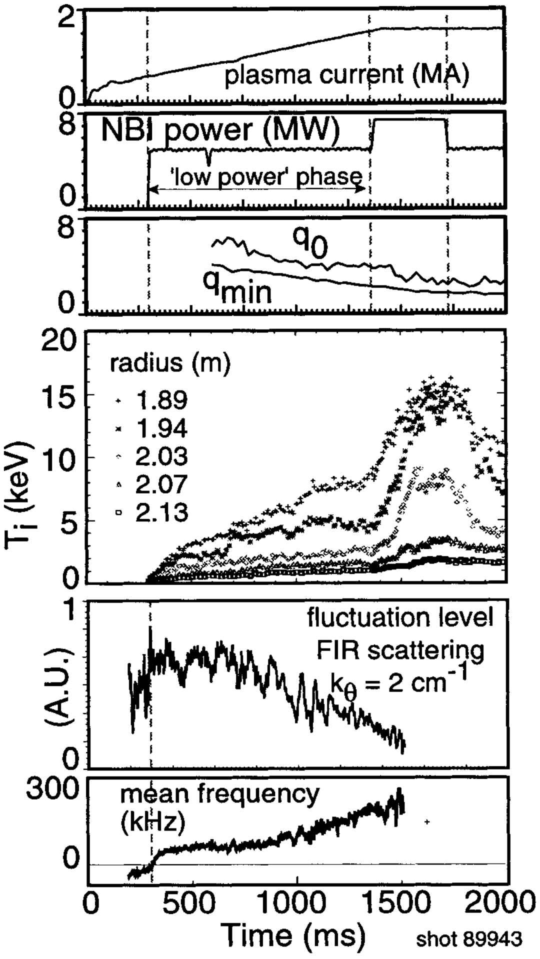

Figure 1. Time evolution of the plasma current, NBI power, central and minimum values of the safety factor (q_0 and q_{min}), the ion temperature measured at various radii during a NCS discharge, the electrostatic fluctuation level in the core, and the fluctuation mean frequency.

At the start of the low-power phase, electrostatic fluctuations in the core and edge exhibit broad wavenumber and frequency dependence, which are characteristic of turbulence. The measured wavenumber ($k_\theta \approx 2$ cm^{-1}) and bandwidth ($\Delta f \sim 50$ kHz) are in a range consistent with drift waves or gradient-driven modes such as the ion temperature gradient instability. Upon the start of NBI at 300 ms, the fluctuation spectrum measured via FIR coherent scattering immediately begins broadening and shifting, the bandwidth eventually becoming 500 kHz to 1 MHz. The frequency measured is the sum of the stationary frame mode frequency and a $E \times B$ Doppler shift arising from the radial electric field, which typically dominates the mode frequency term. Therefore, the mean frequency and frequency broadening of the measured fluctuation spectrum is proportional to the radial electric field and shear in the region where the fluctuations are largest within the sample volume [8].

During the low-power phase of the discharge shown in figure 1, the fluctuation level reduces within the spectral band associated with the core. For example, the fluctuation level associated with poloidal mode $k_\theta = 2$ cm^{-1} is shown in figure 1 as a function of time, beginning in the ohmic phase and continuing through the entire NCS formation phase. Also shown, the bandwidth mean frequency increases steadily for more than 1 s after the start of NBI, indicating that the radial electric field increases in the location where the fluctuations are strongest, changing on a time scale similar to that on which the turbulence reduces. The data implies a reduction in the density fluctuation level $\tilde{n}$ of 30% and a reduction in $\tilde{n}/\bar{n}$ of 50%, confirmed by beam emission spectroscopy (BES) system on DIII-D.

During the low-power phase of the NCS discharge shown in figure 1, the q-profile is inverted and the $E \times B$ profile is strongly sheared. Reduced anomalous transport from reduced turbulence influences the radial electric field evolution by (1) reducing radial diffusion of angular momentum allowing greater rotation gradients to exist and (2) allowing increased pressure which contributes to E_r through radial force balance. Reduced turbulence results in an even stronger shear rate within the transport barrier and this further suppresses turbulence. Therefore, the fluctuations, $E \times B$ shear, and transport are linked causally in a cycle whose ultimate state possesses high $E \times B$ shear and low transport.

When additional NBI is applied late during the discharge, the fluctuation level in the core decreases even further. The greatest reduction occurs in the portion of the fluctuation spectrum associated with the plasma core, as edge fluctuations are relatively unchanged despite large changes in rotation. Figure 2 shows the fluctuation spectrum measured at three different times by FIR scattering during an interval bracketing the start of high-power NBI heating. Core turbulence is virtually quenched within 200 ms of the start of the high-power phase and the energy confinement increases and reaches a maximum value shortly after the minimum in the fluctuation level. If the injected power is greater than the H-mode power threshold, an L- to H-mode transition occurs which is accompanied by the rapid suppression of edge fluctuations [9] and the broadening of the density profile with a steep edge gradient. The fluctuation level in the core in this phase of the discharge is the lowest measured for such a level of auxiliary heating in DIII-D.

An unexpected and unusual feature observed in the turbulence evolution was a ‘bursting’ or intermittent nature to the fluctuation level as it reduced, with the burst cycle varying from less than 1 ms to more than 20 ms (see figure 3). Typically, a final quiescent state is reached wherein the fluctuation level is virtually undetectable, although small transient bursts are observed regularly every 1 to 10 ms. Similar phenomena were observed during the ELM-free phase of VH-mode discharges, wherein the bursts were referred to as momentum transfer events (MTEs) in reference to their anomalous transient enhancement of radial diffusion of toroidal rotation [10]. The intermittent nature of the turbulence reduction is also very similar to that observed in the edge during the ‘dithering’ phase of the L- to H-mode transition seen in many tokamaks. The dithering in ASDEX was attributed to limit cycle oscillations when the injected power was at or just above the threshold power required to drive the discharge into the H-mode [11]. These examples are all associated with a transition to a

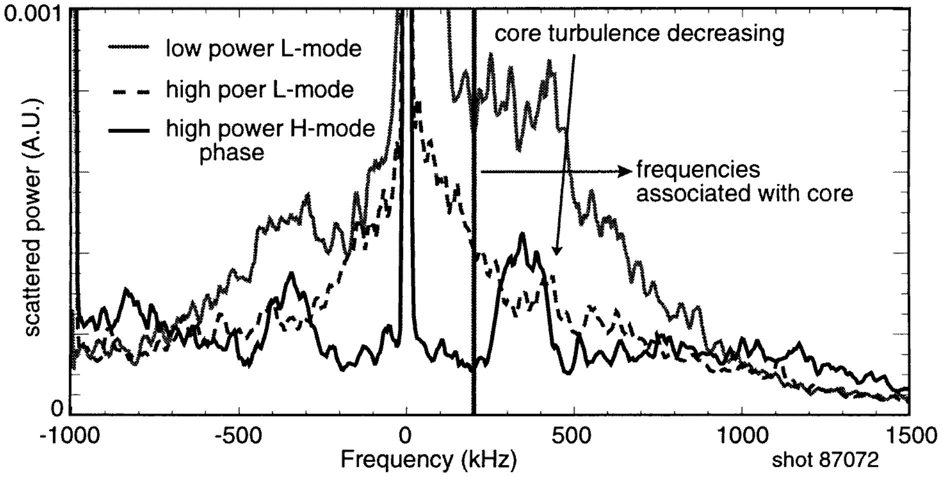

Figure 2. Reduction of turbulence at the start of the high-power heating phase. Additional power is applied at 1400 ms, after which the core turbulence reduces significantly. After 1600 ms, the discharge is in the H-mode and the edge turbulence has been suppressed.

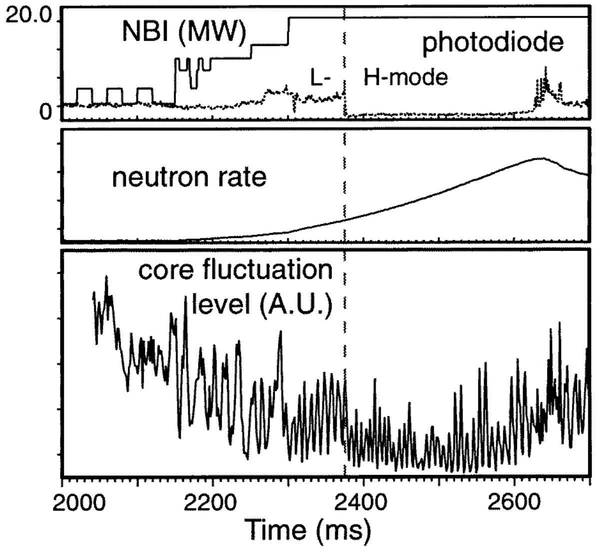

Figure 3. Integrated fluctuation level during expansion of the internal transport barrier of a NCS discharge. Bursts in the fluctuation level are observed as the total level reduces significantly.

higher confinement, lower turbulence plasma state and likely result from analogous physical principles associated with marginal stability of a feedback cycle.

Owing to the simultaneous presence of very large radial electric fields, reduced turbulence, and improved energy and particle confinement in core barrier discharges, $E \times B$ turbulence suppression is the central element of a comprehensive transport model applicable to the experimental evidence [4]. The shearing rate associated with the radial electric field in the core is given by [12]

$$\omega_{\mathrm{E}} = \left| \frac{(RB_\theta)^2}{B} \frac{\partial}{\partial \psi} \left(\frac{E_r}{RB_\theta} \right) \right|$$

and is large enough, even in the low-power formation phase shown in figure 1, to reduce turbulence in the core. It rises to 100–200 kHz, which is comparable to the growth rate predicted for the most unstable drift-ballooning mode calculated by a gyrokinetic stability code under these discharge conditions [13].

3. Summary

In summary, suppression of electrostatic turbulence is closely associated with the evolution to higher performance in NCS discharges. During the low-power phase of the discharge the core electrostatic turbulence reduces steadily over a 1 to 2 s interval. The q-profile is inverted and the radial electric field becomes strongly sheared in the region where the fluctuations are strongest. During this period, a thermal transport barrier forms in the plasma core [3], setting up the conditions to achieve high performance. During the subsequent high-power phase of the discharge, virtually all remaining core turbulence is suppressed and the ion thermal diffusivity reduces to near its neoclassical value in the plasma core. In order to extend the confinement properties of this discharge configuration, the evolution of the pressure profile must be closely controlled so as not to allow the instability drive normally associated with steep gradients to exceed the shear damping as the barrier expands.

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